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Innovation for Climate chAnge mitigation:
a study of energy R&d, its Uncertain
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Icarus expert elicitation reports

Electric drive vehicles

Short Technical Report from the ICARUS survey on the current state and future development

by Valentina Bosetti, Michela Catenacci, Giulia Fiorese, Elena Verdolini

September 2011

Number 03

Fondazione Eni Enrico Mattei

erc

Issue:
no. 3 – Preliminary version
September 2011

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Short Technical Report from the ICARUS survey on the current state and future development

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ICARUS "Innovation for Climate chAnge mitigation: a study of energy R&d, its Uncertain effectiveness and Spillovers" is a three-year (2010-2012) European Research Center (ERC) Starting Grant funded by the European Commission under the umbrella of the 7th Framework Programme.

Thank you again for the time you have devoted to the ICARUS survey. It is greatly appreciated as it has allowed us to collect a wealth of information, which will prove very useful in assessing the potential of electric drive vehicles

Table 1: List of experts participating in the survey

Name and Surname	Affiliation	Country
Michel Armand	Université de la Picardie	France
Pierpaolo Cazzola	International Energy Agency	-
Damien Crespel	Société Véhicules Electrique	France
Claudio Fonsati	Micro-Vett	Italy
Sergio Leonti	FIAT	Italy
Giuseppe Lodi	FIAMM	Italy
Adolfo Perujo y Mateos del Parque	Joint Research Centre	EU
John L. Petersen	Fefer Petersen & Cie	Switzeland
Vittorio Ravello	FIAT	Italy
Bruno Scrosati	Università degli Studi di Roma “La Sapienza”	Italy
Patrice Simon	Université Paul Sabatier	France
Jean Marie Tarascon	Université de la Picardie	France
Christian Thiel	Joint Research Centre	EU
Margaret Wohlgahrt-Mehrens	ZSW ULM	Germany
Karim Zaghib	Ireq	Canada

Please note that the numbers associated to the experts in the paper are randomly assigned.
Note also that the two experts from FIAT filled in just one questionnaire.

Introduction

The present document provides a preliminary analysis of the results of the expert elicitation survey, carried out as part of a 3-year ERC-funded project on innovation in carbon-free technologies (ICARUS - Innovation for Climate chAnge mitigation: a study of energy R&D, its Uncertain effectiveness and Spillovers - www.icarus-project.org).

Figure 1 provides a graphical representation of the main electric drive vehicles (EDVs), which have been considered in the expert elicitation process. Throughout this report, we will refer to the EDVs listed in Table 2.

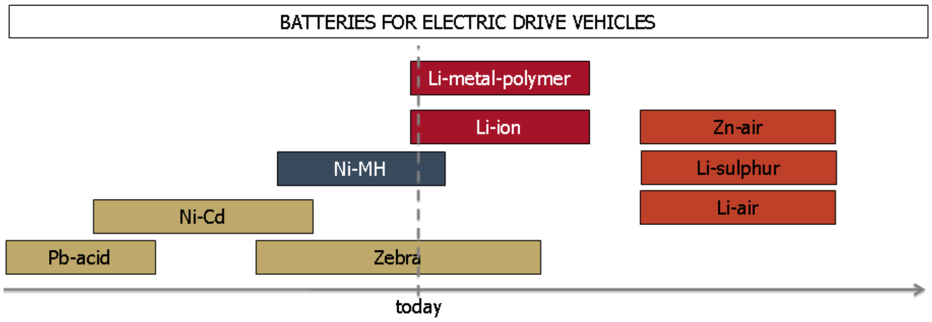

Figure 1: Technology paths that have been assessed in the interviews with the experts

Table 2: Classification of electric drive vehicles by function

Electric Drive Vehicle	Acronym	Functional capabilities provided by battery
Battery Electric Vehicle	EV	Entirely electric power and propulsion engine with grid-charged electricity
Plug-in Hybrid Electric Vehicle (*Plug-in HEV*)	PHEV	Full HEV capabilities plus electric range with grid-charged electricity
Hybrid Electric Vehicle	HEV	

Figure 2 illustrates the origin of the experts participating in the study and shows the heterogeneity of the cluster of experts, which was composed of 3 experts from institutions, 5 from universities and 6 from the private sector.

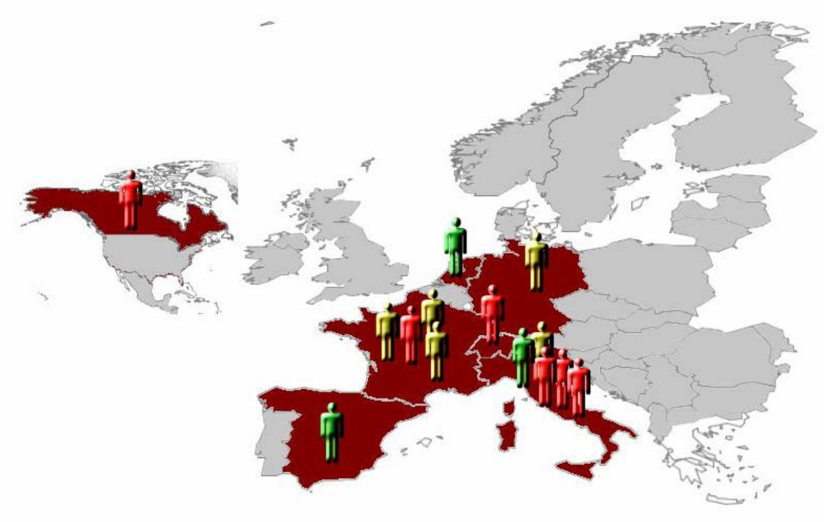

Figure 2: Geographical map of the area of origin of the experts and their professional sector. The individual figures over each country indicate the number of experts per country, while the colours highlight their professional sector: green = institution, yellow = academia, red = private sector.

The level of expertise of the selected experts, using the self-evaluation exercise within the elicitation survey, is shown in Figure 3. The scatter plot area can be read as follows: (i) the high/left quadrant, identifies experts with lower coverage across the different types of technology and a high level of specialisation, (ii) the high/right quadrant, includes experts with high coverage and high specialisation; (iii) the low/right quadrant, includes experts with high coverage and relatively scarce specialisation; and (iv) the low/left quadrant includes experts characterised by low coverage and low specialisation. The ordination shows that experts are almost equally divided between a higher (Specialization Index > 50%) and lower (< 50%) degree of specialisation; almost all experts have a high level of coverage (Coverage Index >50%).

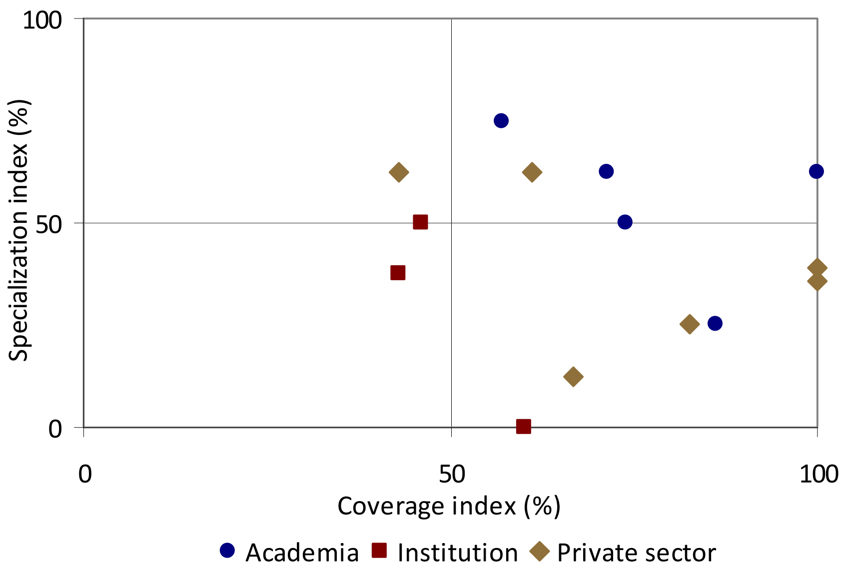

Figure 3: Direct ordination of the 14 experts based on the Coverage Index and the Specialisation Index.

Figure 4 shows the level of expertise across all experts for each technology. All of the different types of batteries are covered by at least one expert declaring a high level of expertise. The highest levels of expertise are concentrated on Li-ion and LMP batteries, which are the two emerging technologies. Many experts have a medium expertise for Ni-MH and Zebra batteries. Li-air, Li-sulphur and Zn-air are represented by a majority of experts with low expertise. For technologies other than the ones mentioned, two experts indicated super-capacitors, two other experts indicated advanced lead batteries and one expert indicated Li Redox Organic.

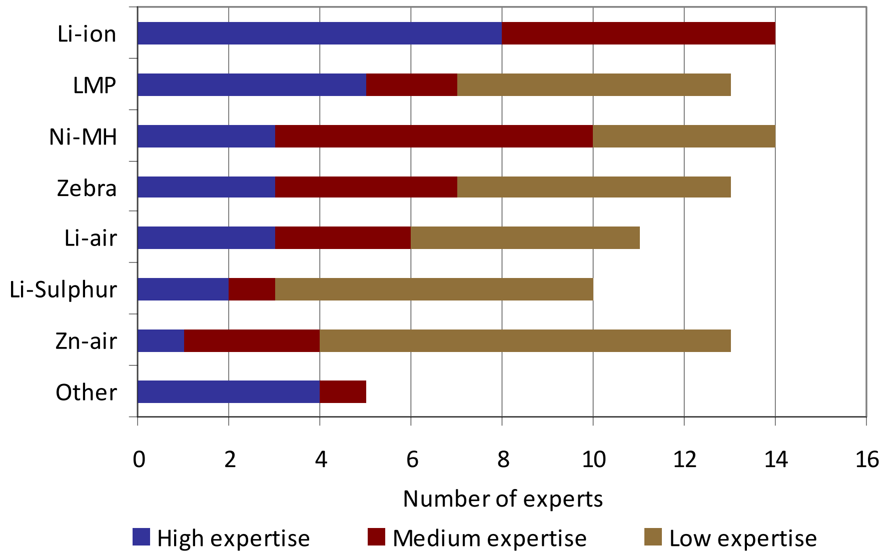

Figure 4: Distribution of the experts in three classes of expertise (High expertise: max level of knowledge >3; medium expertise: max level of knowledge =3; Low expertise: max level of knowledge <3) among all the technological paths.

Technical potential of batteries for EDVs

The assessment of the possible drivers for future variations in the cost of EDVs started with an analysis of the current technical characteristics of the different battery technologies. The experts provided important insights on the specific conditions which would lead batteries for EDVs to commercial success, and also identified the stages of the RD&D process which had to be improved to overcome existing bottlenecks. Figure 5 shows how each expert evaluated the status of each technology: the bigger the circle, the higher the need for improvements. In particular, experts were asked to evaluate the status of a technology by assigning a value from 1 (current level is excellent) to 3 (substantial advances are needed). The highest requirements for improvements are for Li-air, Li-sulphur, Zn-air, LMP and Zebra batteries. Li-ion batteries are also evaluated as needing advances. It emerges that Ni-MH batteries are considered the closest to an excellent current level, however many experts believe that advances are still needed.

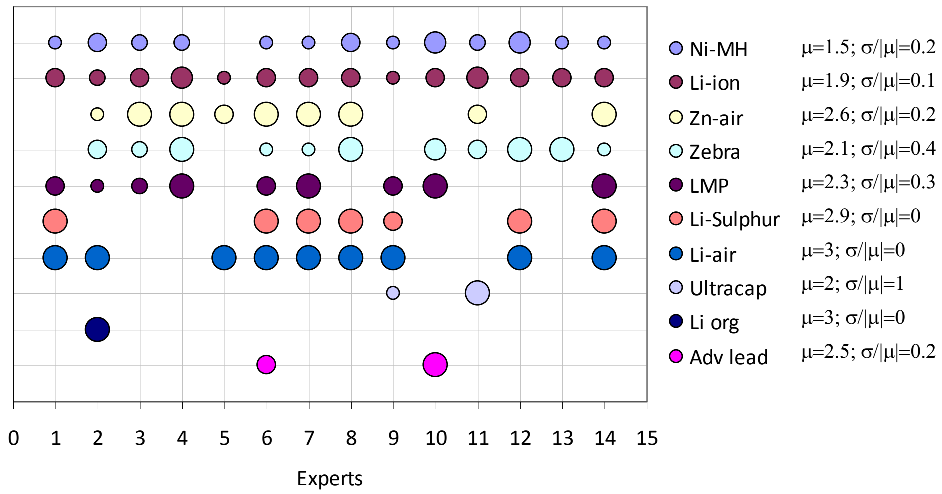

Figure 5: Current maturity level of the different batteries for electric drive vehicles (row) assigned by each expert (column). To evaluate the status of a technology, a number from 1 (status is excellent) to 3 (significant advances are needed) was assigned. Both the average and the coefficient of variation are provided.

To identify the most important drivers of the variations in the costs of batteries, we asked each expert to comment on the current level of technical development of the proposed technological options. Experts were asked to identify the main bottlenecks which currently represent barriers to cost reductions and to specify what type of RD&D would be most needed. Table 3 reports keywords that were mentioned by at least four experts when discussing barriers and issues connected to each of the technological options. The main bottlenecks for Ni-MH are related to the energy density and to the processing costs of the battery. Costs, together with safety issues, are relevant for Li-ion batteries as well. The low power density is a main issue for both Zn-air and Zebra batteries. For Li-sulphur and Li-air, experts did not point out specific barriers, rather they signalled that there is still need to prove their viability and that they are a long-term project.

Table 3: Keywords mentioned by at least 4 experts

Batteries	Bottlenecks
Ni-MH	Energy density Processing cost
Li-ion	Safety Cost
Zn-air	Power density Rechargeability Cycle life
Zebra	Power density High temperature

Experts were asked to define their optimal allocation of the RD&D budget over the 2010-2030 period in order to make biofuel technologies commercially successful in 2030. The budget was conventionally expressed in 100 chips that the experts had to distribute among the different batteries (results are reported in Figure 6). By far, the highest allocations of the budget are devoted to improving Li-ion batteries. Two experts assigned a high share of their budget to Ni-MH while, on the other hand, four experts didn't assign any chip to this battery. Li-air is the other technology that receives on average the highest number of chips from each expert. Experts allocated some chips to other technologies such as super-capacitors (55 chips), Li Redox Organic (20 chips) and advanced lead (10 chips). One expert allocated 10 chips to basic research in general, not specifically focused on any of the technologies mentioned, and another expert allocated 20 chip to other technologies without any further detail.

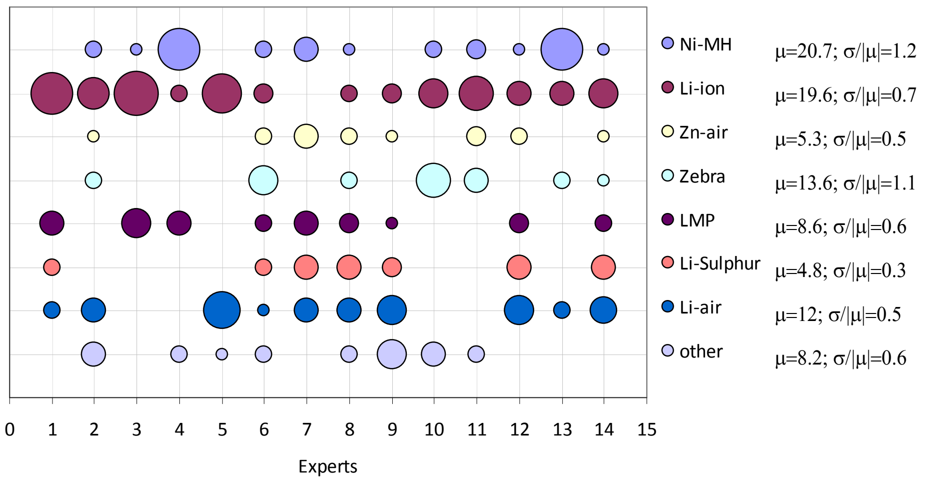

Figure 6: Allocation of the RD&D budget over the 2010-2030 period to make batteries for EDV commercially successful in 2030. The budget is conventionally expressed in 100 "chips" per expert (column), to be distributed among the different technologies. For each battery (row) both the average and the coefficient of variation are provided.

Notwithstanding the large difference across experts, it is informative to look at the aggregate data. Figure 7 provides information about the suggested type of RD&D needed between basic, applied and demonstration, summing the chips allocated by all the experts. Almost one third of all the budget across all experts is devoted to Li-ion batteries; this budget should be used for applied and demonstration activities, but also basic research is not disregarded. The RD&D budget for Ni-MH batteries should be used for applied and demonstration activities, while basic research receives a small share of the overall budget. As for innovative technologies, a substantial portion of research funds for Li-air and Li-sulphur should be used for basic research.

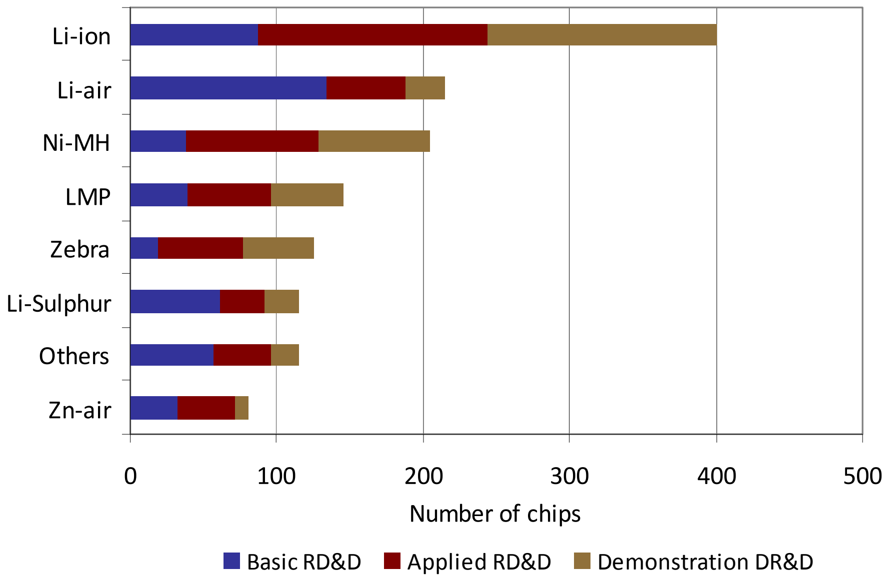

Figure 7: Sum of the RD&D allocated by all experts among different technologies and budget breakdown among basic, applied and demonstration RD&D.

RD&D effectiveness on future costs of batteries for EDVs

Figure 8 and Figure 9 show experts' expected costs in 2030 (90th percentile, 10th percentile and 50th percentile, "best guess") for EVs and PHEVs respectively under 3 different RD&D scenarios. In the first scenario the current annual level of RD&D would not change until 2030. In the second scenario, the investment in RD&D for EDVs technologies would increase by 50% until 2030, and in the third scenario the investment in RD&D would increase by 100% in the next 20 years.

Estimates of the expected cost of batteries in 2030 (Figure 8 and Figure 9) indicate a high degree of uncertainty and variance among the experts. In the case of batteries for EVs, 7 out of 14 experts who answered the question provided an expected cost (for the best guess) between 200 and 400 $/kWh, while 6 other experts provided a cost higher than 400, and in one case up to 750 $/kWh. A similar pattern can be recognised in the expected costs of batteries for PHEVs. On average across all the experts, the cost of batteries for PHEVs is expected to be about 50 $/kWh higher than the cost of batteries for EVs. Looking at the answers of each expert the difference in cost between batteries for EVs and PHEVs varies from zero to up to 160 $/kWh.

According to several experts, the uncertainty doesn't consistently decrease with a higher RD&D investment. Specifically, according to five experts, both in the case of EVs and PHEVs, the cost of the battery does not depend on the level of RD&D funding. According to these experts, in fact, the abatement of costs depends more on the increase in the production volumes of the batteries and the ability of the industries to develop and produce in large scale what has been discovered by researchers. This link between research and industry is seen as particularly weak in Europe, where research in the field is excellent, but exploitation at the industrial level is poor.

According to Kromer and Heywood[1], the projected 2030 battery cost is expected to be 200÷250 $/kWh for EVs and 320÷420 for PHEVs (shaded areas in Figure 8 and Figure 9). A more recent review of battery costs[2] estimates for 2020 values of 375÷500 $/kWh for EVs and 675÷1120 $/kWh for PHEVs. As for EVs, only the estimates provided by the most optimistic experts (five out of fifteen) were in agreement with those indicated in the 2030 literature. The rest of the experts were much more conservative. In addition, it is interesting to point out that the value of 150 $/kWh, which is widely[1] assumed as the commercialization target, is outside the range of all estimates provided by the experts, even assuming increased RD&D scenarios.

Eight out of fourteen experts provided the estimate of expected costs for lithium technologies, which are considered to be the most promising for the next decades. Experts 10, 11 and 14 in Figure 8 and Figure 9 were referring to a mix of technologies; in particular expert 10 referred to Li-ion and Zebra batteries. One expert did not provide any cost.

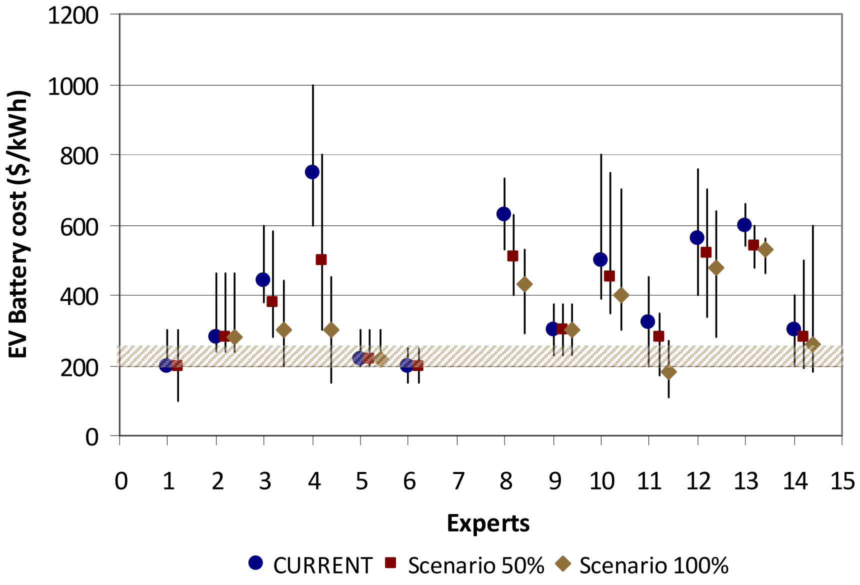

Figure 8: Estimates of the cost of EV batteries ($/kWh) in 2030, under three different RD&D funding scenarios. The shaded area represents the projected 2030 EV battery cost range as estimated in Kromer and Heywood[1].

[1] Kromer, M.A., and J.B., Heywood, Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet, MIT Laboratory for Energy and the Environment, Cambridge, Massachusetts, 2007.
[2] Cheah, L., and J., Heywood, The Cost of Vehicle Electrification: A Literature Review, Sloan Automotive Laboratory, Massachusetts Institute of Technology, April 2010.

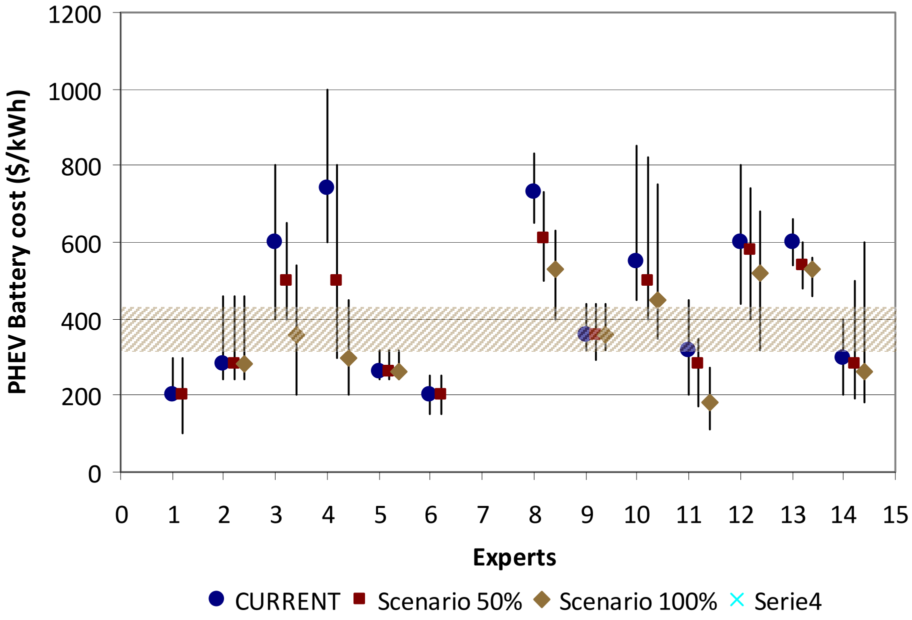

Figure 9: Estimates of the cost of PHEV batteries ($/kWh) in 2030, under three different RD&D funding scenarios. The shaded area represents the projected 2030 PHEV battery cost range as estimated in Kromer and Heywood[1].

Diffusion of batteries for EDVs

In the fourth section of the questionnaire, we asked the experts to indicate which geographical area of the world had the highest probability of being the first to reach commercial success. According to the experts' assessment the first area to reach the breakthrough would be Japan (as indicated by 8 experts), followed by China (7 experts), Korea (3 experts), USA and Europe (each indicated by 1 expert).

The experts then considered how the dynamics of technology transfer between countries and regions of the world could affect the choice to support internal RD&D programs. The majority of the experts (12) affirmed that the current conditions reflect a relatively successful cooperation among different countries, which results in important knowledge spillovers. However, they agreed on the binding need for each country to invest in its own RD&D program in order to develop absorptive capacity and therefore to be ready to adopt breakthrough technologies developed by other countries.

Negative externalities and changes in the transport sector

Experts were asked to identify the potential negative externalities on the environment and society as a whole which might derive from the diffusion of EDVs. There was very high agreement among experts, since almost all of them mentioned the following externalities and negative impacts: the carbon intensity of the electricity used to recharge the batteries; the need to develop adequate recycling of exhausted batteries; the impacts derived from mining for the extraction of metals needed for the production of the batteries. Few experts added that the process for producing the batteries is also extremely energy-intensive, and might thus offset the benefits of using EDVs instead of

ICE vehicles. Other issues that emerged are related to the toxicity of the battery-producing process and the dependence on a small number of countries for the supply of critical materials.

Experts were also asked to discuss what innovations they believed would be developed in the transport sector in the future. For example, if they expected innovations concerning transport infrastructure to impact in some crucial way the choice for EDV. According to several experts, the successful deployment of electric transportation is conditional upon the availability of adequate infrastructures, such as places where batteries can be recharged. Three experts also mentioned the possibility of developing "fuelling stations" where instead of recharging, exhausted batteries are swapped with full ones (*battery swap*). Nine experts believe that in the future we will experience a significant change in behaviour and habits concerning driving. On one side, public transportation, and in particular electrified transport, will be increased to satisfy the demand for city travelling. On the other side, the pattern of vehicles' ownership will change and car-sharing or similar activities will be common.

Non-technical barriers to diffusion

The last section of the questionnaire assessed the crucial role of market diffusion for the success of EDVs and their competitiveness with ICE. Experts were asked to discuss and evaluate the importance of a set of potential barriers and then suggest other barriers they considered relevant. Figure 10 shows all the identified barriers and provides a ranking of their importance together with the suggested solution.

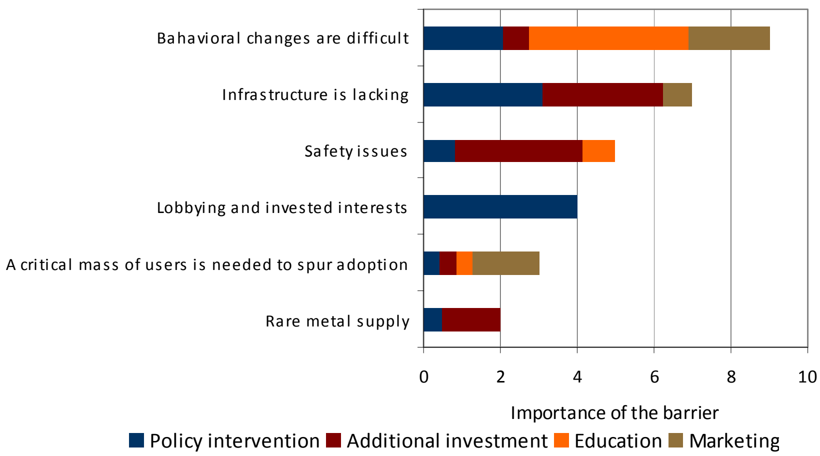

Figure 10: Factors which could represent non-technical barriers to the diffusion of EDVs and potential solutions to overcome the barriers. The importance of the barrier is given by the number of experts who indicated the barriers with maximum importance.

The most important barrier is the difficulty of changing the behaviour of car drivers. This is mainly related to the limited driving range of EVs that requires a different pattern of usage of the vehicles. Education and marketing are the preferred way to overcome such barriers. The lack of adequate infrastructure is the second most important barrier to EDVs diffusion. In this case, policy interventions and additional investments are the suggested solutions. Safety is the third barrier for importance; almost all experts considered safety crucial for the commercial production of EDVs, thus implying that a vehicle on the market must be safe or it would not be commercialized. Lobbying and invested interest, the need of a critical mass of users and metal supply were all evaluated to be low importance barriers.

Diffusion trends

Assuming that in 2030 EDVs are technically ready to compete with conventional ICE vehicles, we asked the experts to provide a probability of three specific penetration rates of EDVs. Specifically, we asked the experts to provide the probability associated to three scenarios corresponding to three penetration rates (20, 50 and 70%) of EV and PHEV car sales by 2050. Moreover, we asked to distinguish between OECD, fast-growing and developing country groups. There is a lot of variance among the answers provided by the experts, as shown by the three graphs in Figure 11. For OECD countries, overall experts assign almost the same probability to all three scenarios; one can observe, in fact, that there are pessimistic opinions (experts 3, 4, 11, 14), optimistic opinions (experts 5, 7, 8 and 9) and opinions in between (all other experts). Only eight experts provided probability of occurrence of the three scenarios in fast-growing countries; also in this case experts are equally divided in more optimistic, pessimistic and in between. Finally, in the case of developing countries, experts generally agree that the low-diffusion scenario is the one with the highest probability.

We also asked what experts thought could be the ceiling to the diffusion trend of EVs and PHEVs. Four experts indicated a ceiling higher than 75% and three experts indicated a value between 50% and 75%. The other experts were more conservative: according to one expert the ceiling is at 33%, while four experts thought the ceiling was lower than 20%. The remaining two experts did not respond to this question.

The main reason behind the figures provided is given by the driving range of EDVs that limits the possibility of using EDVs in many occasions, from the daily round trip from home to office, to the occasional road trip. Few experts mentioned as a factor limiting the diffusion of EDVs the existence of other technologies that will also have a role in the transport sector (such as hydrogen).

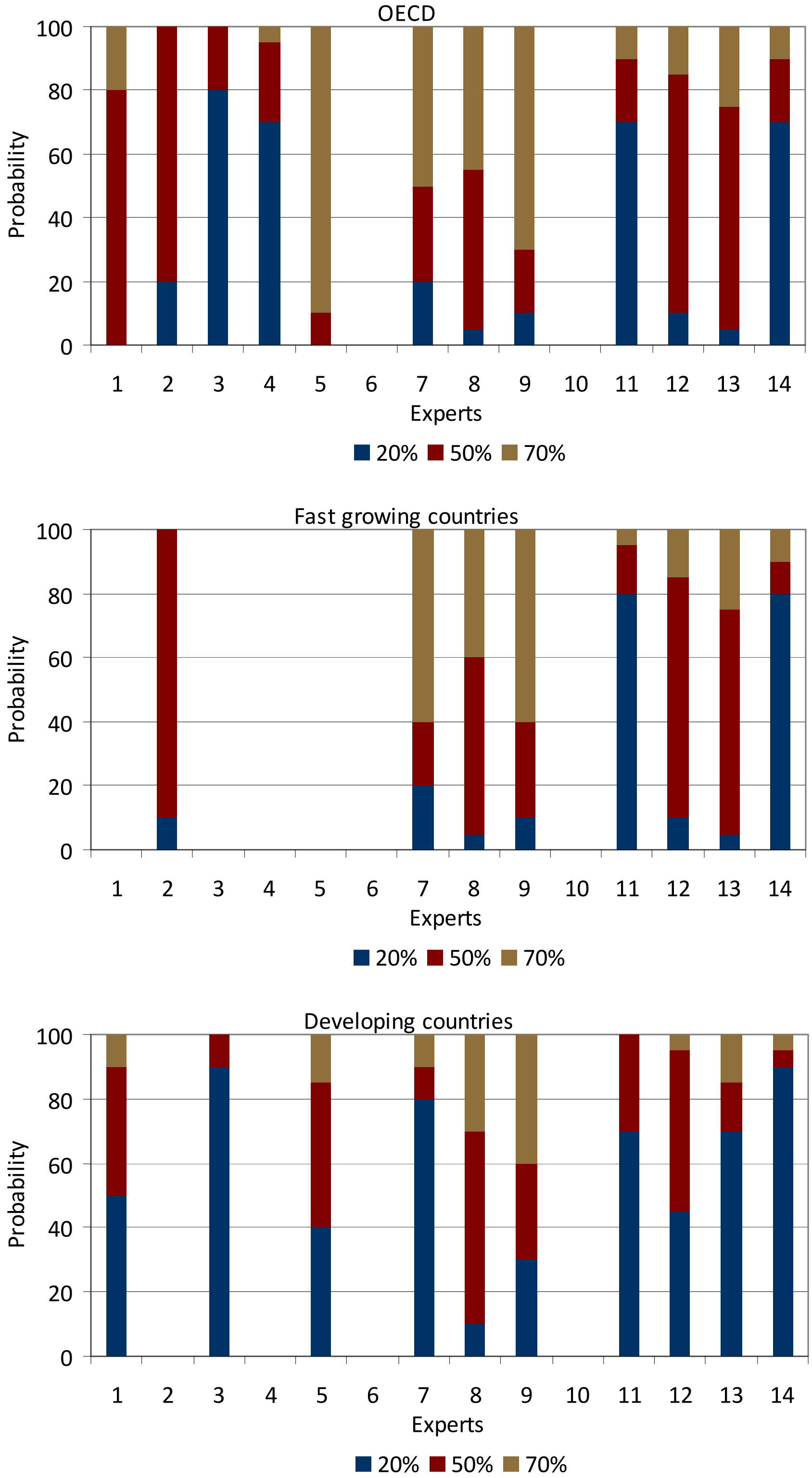

Figure 11:Probability of 3 different penetration rates of EVs and PHEVs car sales in 2050 (OECD, fast-growing and developing countries).